

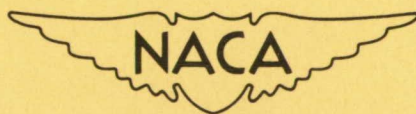
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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THE HYDRODYNAMIC CHARACTERISTICS OF AN
ASPECT-RATIO-0.125 MODIFIED RECTANGULAR FLAT
PLATE OPERATING NEAR A FREE WATER SURFACE

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SUMMARY

An investigation has been conducted to determine the hydrodynamic force characteristics of an aspect-ratio-0.125 modified flat plate mounted on a single strut and operating at several depths of submersion. Comparisons were made between these data and similar data previously obtained on flat plates having aspect ratios of 1.00 and 0.25 and with various aerodynamic theories. These comparisons indicate that decreasing either the aspect ratio or depth of submersion decreased the lift coefficient, drag coefficient, and lift-drag ratio. The center of pressure moved rearward with decreasing aspect ratio and forward with decreasing depth of submersion except for the aspect-ratio-0.125 plate at angles of attack above 8° . For these angles, the center of pressure moved rearward for decreasing depth of submersion.

Cavitation at the leading edge caused a gradual decrease in lift coefficient and a gradual increase in drag coefficient. The planing-bubble type of high-angle separation caused sharp decreases in lift, drag, and moment coefficients. The ventilation boundaries defining the start of the high-angle separation moved to higher speeds and higher angles as the aspect ratio was decreased.

A theory obtained by modifying Falkner's vortex-lattice theory, which had shown good agreement at all angles for aspect ratios of 1.00 and 0.25, agreed with the data for the aspect-ratio-0.125 plate except at angles above 16° where the predicted lift proved to be too high.

INTRODUCTION

Results of a hydrodynamic investigation of submerged rectangular flat plates having aspect ratios of 1.00 and 0.25 were presented in reference 1. The purpose of the investigation described in this paper was

to extend the range of data available to include that for an aspect ratio of 0.125.

Experimental data were obtained in Langley tank no. 2 by using a modified rectangular flat plate having an aspect ratio of 0.125, mounted on a single strut, and operating at several depths of submersion. Lift, drag, and pitching moment about the trailing edge were obtained and the effects of certain flow phenomena which were observed during the tests are discussed. Comparisons of these data with the data from reference 1 are presented; these comparisons show the effects of aspect ratio on the hydrodynamic characteristics. The lift data obtained at large depths, a condition which approximates the infinite medium of the aerodynamic case, are compared with values predicted by various aerodynamic theories.

SYMBOLS

C_D	drag coefficient, $\frac{D}{\frac{1}{2}\rho V^2 S}$
C_L	lift coefficient, $\frac{L}{\frac{1}{2}\rho V^2 S}$
C_m	pitching-moment coefficient about trailing edge, $\frac{M}{\frac{1}{2}\rho V^2 S c}$
c	chord of lifting surface, ft
D	drag, lb
L	lift, lb
M	moment about the trailing edge, ft-lb
S	area of lifting surface, sq ft
V	forward velocity, ft/sec
ρ	density, slugs/cu ft

The subscript 6 denotes a depth of submersion of 6 inches.

MODEL, APPARATUS, AND PROCEDURE

The model used was a modified rectangular flat-plate surface with an aspect ratio of 0.125 mounted on a single strut. Like the models used in the tests of reference 1, this lifting surface had the leading edge rounded to a 2:1 ellipse and the afterportion beveled so that the included angle at the trailing edge was 10° . A drawing of the model is shown in figure 1.

The strut used in this investigation is the same as that used in reference 1 and is mounted in the same location relative to the lifting surface. The strut, which had an NACA 66₁-012 airfoil section, was mounted so that the station 1.182 inches back of the leading edge of the strut was a distance equivalent to 45 percent of the lifting surface forward of the trailing edge of the surface. The strut was mounted perpendicular to the plate and had no fillets at the intersection with the upper surface. Both the model and the strut were made of stainless steel and polished to a smooth finish. Tests were made by using the Langley tank no. 2 carriage with strain-gage balances to measure independently the lift, drag, and pitching moments. The pitching moment was measured about an arbitrary point above the model and the data thus obtained were used to calculate the pitching moments about the trailing edge.

All tests were run with a windscreen which reduced the aerodynamic tares and aerodynamic effects on flow patterns to negligible values. Before each run, measurements were taken in the "at rest" condition with the model submerged and the values thus obtained were subtracted from the data obtained during the run; therefore, the buoyancy of the model and strut was not included in the data. The hydrodynamic strut tares were not subtracted from the data.

Force measurements were made at constant speeds for fixed angles of attack and depths of submersion. The depth of submersion is defined as the distance from the undisturbed water surface to the point on the model nearest the surface. Tests were run at four depths of submersion (0.5, 1.0, 3.0, and 6.0 inches) over a range of angle of attack from 0° to 20° . The range of speed covered at each depth and angle of attack was determined by the capacities of the balances.

The change in angle of attack due to structural deflection caused by the forces on the model was obtained in the calibration of the balances and the data were adjusted accordingly. The depth of submersion was adjusted during the run to keep variations in this parameter to a minimum. The estimated accuracy of the measurements is as follows:

Angle of attack, deg	±0.1
Velocity, ft/sec	±0.2
Depth of submersion, in.	±0.05
Lift, lb	±0.25
Drag, lb	±0.10
Moment, ft-lb	±0.5

Forces and moments were converted to the usual aerodynamic coefficients by using a measured value of the density of 1.968 slugs per cubic foot. The kinematic viscosity measured during the tests was 1.42×10^{-5} feet squared per second.

RESULTS AND DISCUSSION

Force Data

The data obtained are presented in figures 2 to 4 as plots of lift, drag, and pitching moment about the trailing edge against angle of attack with speed as a parameter. Data are presented for each of the four depths investigated.

The discontinuities in the drag curves at low angles of attack correspond to similar discontinuities noted in reference 1. The flow changes which cause these discontinuities were not visible during the running of the tests. At the high angles and shallow depths, the discontinuities in lift, drag, and moment curves are due to the presence of the planing bubble described in reference 1.

Visible Flow Changes and Their Effects

Cavitation.- Cavitation at the leading edge occurred at high speeds for all depths. These high speeds could be reached only at very low angles of attack; therefore, the effects of cavitation were not readily evident in the data plots. Figure 5 shows the effect of the formation of cavitation on the lift, drag, and moment coefficients for an angle of attack of 2° and a depth of 0.5 inch. The coefficients seem to have reached a fairly constant value when the cavitation started. As the speed increased, the cavitation became more severe and caused the lift coefficient to decrease and the drag coefficient to increase. The moment coefficient showed only a very slight change with increasing speed after the start of cavitation. These effects were the same as those found for the plates having aspect ratios of 1.00 and 0.25 (ref. 1).

Ventilation.- The planing bubble occurred at the high angles and shallow depths as it had in the tests described in reference 1. Air

was observed to enter the trailing vortices back of the model. As the speed increased, the air proceeded forward along a helical path inside the vortices until it reached the model; at that point, separation took place. This separation took the form of the planing bubble, an air bubble surrounded by a film of water in such a manner that no water touches the upper surface of the model. The white water which occurred for the aspect-ratio-1.00 surface did not occur for the aspect-ratio-0.125 surface.

The effect of the formation of the planing bubble on the lift, drag, and moment coefficients is shown in figure 6 for an angle of attack of 16° and a depth of submersion of 0.5 inch. All three coefficients decreased as the speed at which the planing bubble formed was approached. As the planing bubble formed, all three coefficients experienced a sharp decrease, primarily because of the loss of upper-surface lift. These effects are the same as those found for the plates having aspect ratios of 1.00 and 0.25.

The ventilation boundary for the aspect-ratio-0.125 flat plate at 0.5-inch depth is shown in figure 7 where it is compared with the boundaries for the plates having aspect ratios of 1.00 and 0.25. The boundaries for the three aspect ratios are similar in shape but are displaced to higher speeds and higher angles with decreasing aspect ratio.

Comparison With Data for Other Aspect Ratios

in the Region of Undisturbed Flow

The lift and drag characteristics on a coefficient basis for the three low-aspect-ratio surfaces at a depth of 6.0 inches are shown in figure 8. At this depth, the effect of the free surface on the characteristics is small. The nonlinearity common to low-aspect-ratio surfaces is shown in the plot of lift coefficient against angle of attack. The lift coefficient for a given angle of attack decreases and the nonlinearity increases with decreasing aspect ratio.

The curves of drag coefficient against lift coefficient indicate a slight decrease in drag coefficient for a given lift coefficient with increasing speed and a much greater decrease with the increase in aspect ratio. The lift-drag polars for the higher aspect ratios are presented only for a speed of 10 feet per second because the trends are the same at other speeds. The lift-drag ratios increase with increasing aspect ratio except for the very low lift-coefficient range where the drag discontinuity noted on the data plots apparently has a greater effect for the surfaces of aspect ratio 0.25 and 0.125; thus, the lift-drag ratios for these surfaces become greater than those for the aspect-ratio-1.00 surface.

The effect of changing the depth of submersion on lift coefficient for the three aspect ratios is shown in figure 9. Values of the ratio of the lift coefficient at a given depth to the lift coefficient at a depth of 6.0 inches C_L/C_{L6} are plotted against angle of attack with depth of submersion as a parameter in figure 9(a) and against depth of submersion for an angle of attack of 12° in figure 9(b). The lift coefficient decreased as the free surface was approached, the decrement in lift coefficient becoming less as the aspect ratio was reduced. The reduction in the decrement of lift coefficient in going from an aspect ratio of 0.25 to an aspect ratio of 0.125 was considerably greater than that found in going from an aspect ratio of 1.00 to an aspect ratio of 0.25. The loss in lift was greatest at the lower angles of attack for all three aspect ratios at all depths. The decrement in lift coefficient was considerably reduced as the angle of attack was increased to 12° , at which point it reached a minimum value and changed only slightly with further increase in angle of attack.

The effect of changing the depth of submersion on drag coefficient is shown in figure 10 and is similar to the effect on lift coefficient in that the drag coefficient also decreased as the aspect ratio was reduced. The reduction in decrement in drag coefficient in going from aspect ratio 0.25 to aspect ratio 0.125 was about the same as that obtained in going from aspect ratio 1.00 to aspect ratio 0.25.

Inasmuch as the decrease in drag coefficient was less than the decrease in lift coefficient, the lift-drag ratio for all three aspect ratios decreased as the models approached the free water surface. At the depths investigated, the strut drag was small in relation to the total drag. It might be well to point out, however, that, as the depth increases, the strut drag naturally increases also; thus, at some depth, the lift-drag ratio will start to decrease with increasing depth.

The fact that both the lift and the drag coefficients approach the values of the coefficients at a depth of 6.0 inches more or less asymptotically indicates that at this depth the effects of the free surface may be considered negligible.

The location of the center of pressure as a function of the angle of attack with depth of submersion as a parameter for the aspect-ratio-0.125 flat plate is shown in figure 11. A comparison with similar plots presented in reference 1 for the surfaces having aspect ratios of 1.00 and 0.25 indicated that, in general, the rearward movement of the center of pressure with decreasing aspect ratio and the forward movement with decreasing angle of attack held for the three aspect ratios investigated. Changing the angle of attack had a much greater effect at the low angles, the center of pressure occurring forward of the leading edge at an angle of attack of 2° for all depths tested with the aspect-ratio-0.125 surface. This effect indicates the presence of a suction force on the rear

portion of the bottom of the model, or an increase in negative pressure on the upper surface near the leading edge, or both.

For the higher aspect-ratio surfaces (ref. 1), the center of pressure moved forward with decreasing depth of submersion for all angles of attack. For the aspect-ratio-0.125 surface, this trend held true only at angles below 8° ; above 8° , the center of pressure moved rearward with decreasing depth of submersion.

Comparison With Theory

In order to obtain an exact comparison between the data presented herein and aerodynamic theories, the tares and interferences would have to be eliminated, and corrections would have to be made to account for effects produced by the solid boundaries and by the finite depth of water in the tank. Mainly because of the low aspect ratio of the models and their small size compared with the tank dimensions, however, these factors have only a very slight effect on the lift and were therefore neglected.

As pointed out in the previous section, the free boundary effects of the water surface were negligible at a depth of 6.0 inches. For this reason, a comparison of the lift characteristics at a depth of 6.0 inches with theoretical results from references 1 to 5 is presented in figure 12. The results of Falkner's linear theory (ref. 2) were obtained by using two vortices spanwise and three vortices chordwise for the half wing. The predicted values of this linear theory are much lower than the experimental values for all angles and represent only a fair approximation even for the very low angles. The nonlinear theories of Weinig (ref. 3) and Flax and Lawrence (ref. 4) predict values which are also low when compared with the data but they represent a considerably better approximation than the linear theory. The method presented in reference 1 which is a modification of Falkner's linear theory is in somewhat closer agreement with the data of this investigation except at the very high angles where this method predicts values considerably in excess of those actually achieved. The theory of Bollay (ref. 5) shows excellent agreement over the entire range of angles tested.

The theory of reference 1 was developed to make possible the determination of the lift at large depths and to provide a theory which would be amenable to possible modification by the method of images to account for the effects of the free water surface. Figure 13 presents a comparison of the lift predicted by this theory with tank data from the present tests and those of reference 1 and with wind-tunnel data (refs. 6 and 7). Agreement is excellent for aspect ratios of 1.00 and 0.25 for the entire range of angles investigated and is reasonable for aspect ratios of 0.125 up to an angle of 16° . It may be said, therefore, that this theory is accurate

for aspect ratios between 0.125 and 1.00; thus, it may be considered for use as a base in order to determine a theory to predict the effects of the free water surface for aspect ratios in this range.

CONCLUSIONS

An experimental investigation has been conducted to determine the hydrodynamic force characteristics of an aspect-ratio-0.125 modified flat plate mounted on a single strut and operating at several depths of submersion. Comparisons between these data and similar data obtained previously on flat plates having aspect ratios of 1.00 and 0.25 and with various aerodynamic theories indicated that:

Decreasing the aspect ratio for a given depth of submersion decreased the lift coefficient, the drag coefficient, and the lift-drag ratio and caused a rearward movement of the center of pressure.

Decreasing the depth of submersion for a given aspect ratio decreased the lift coefficient, drag coefficient, and lift-drag ratio. The center of pressure moved forward with decreasing depth of submersion for all angles of attack for the plates having aspect ratios of 1.00 and 0.25 and for angles of attack below 8° for the aspect-ratio-0.125 plate. Above 8° , the center of pressure for the aspect-ratio-0.125 plate moved rearward with decreasing depth of submersion.

Cavitation at the leading edge caused a gradual decrease in lift coefficient, a gradual increase in drag coefficient, and little change in moment coefficient.

The ventilation boundaries defining the start of high-angle separation moved to higher speeds and higher angles of attack as the aspect ratio was decreased. The planing-bubble type of high-angle separation caused a sharp decrease in lift, drag, and moment coefficients.

The comparison with the aerodynamic theories indicated that the theory of Bollay showed the greatest accuracy in predicting the lift for the aspect-ratio-0.125 surface. The theory obtained by modifying Falkner's vortex-lattice theory, which had shown good agreement at all angles for

aspect ratios of 1.00 and 0.25, agreed with the data for aspect ratio 0.125 except at angles above 16° where the predicted lift proved to be too high.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 20, 1954.

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1. Wadlin, Kenneth L., Ramsen, John A., and Vaughan, Victor L., Jr.: The Hydrodynamic Characteristics of Modified Rectangular Flat Plates Having Aspect Ratios of 1.00 and 0.25 and Operating Near a Free Water Surface. NACA TN 3079, 1954.
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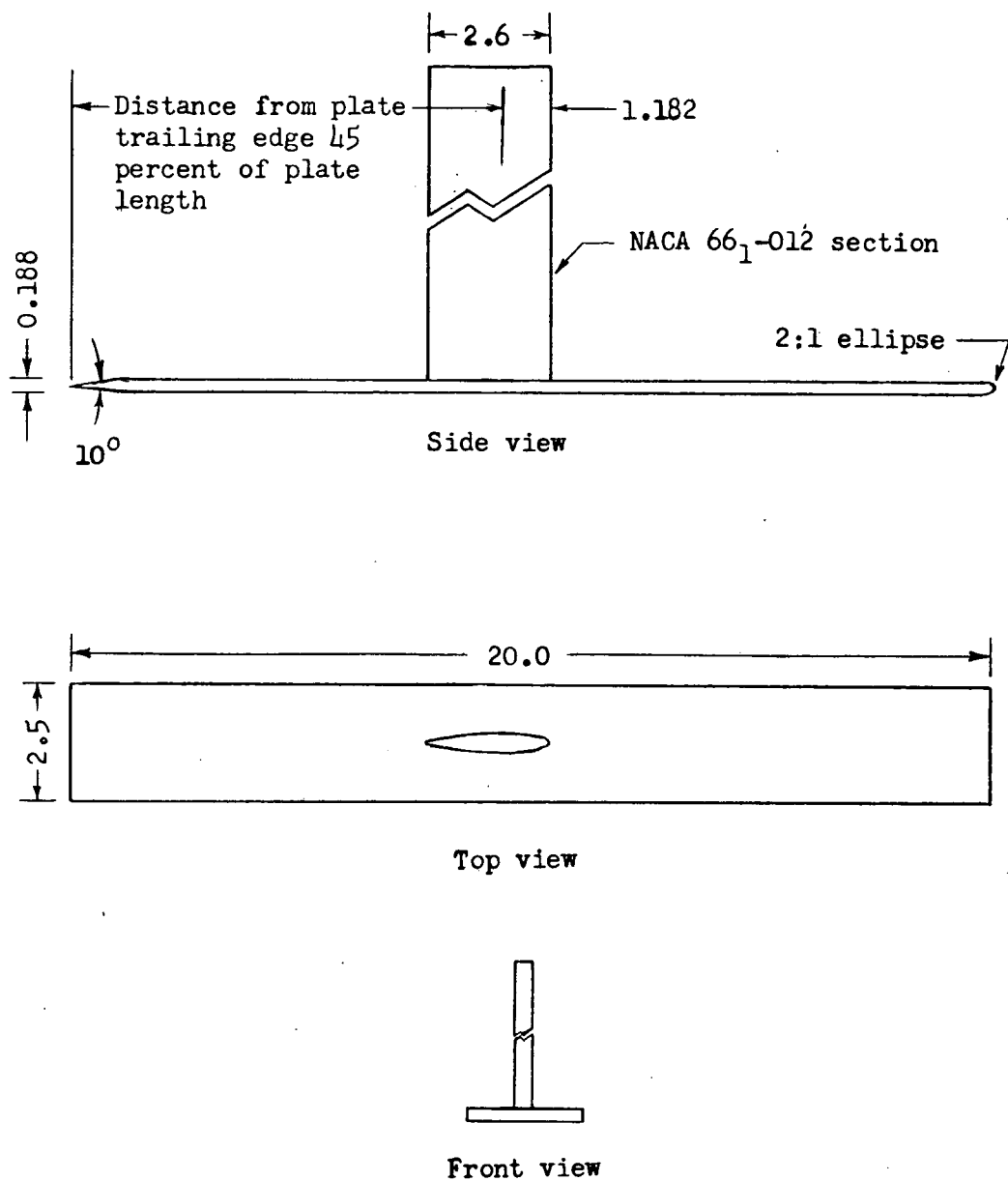
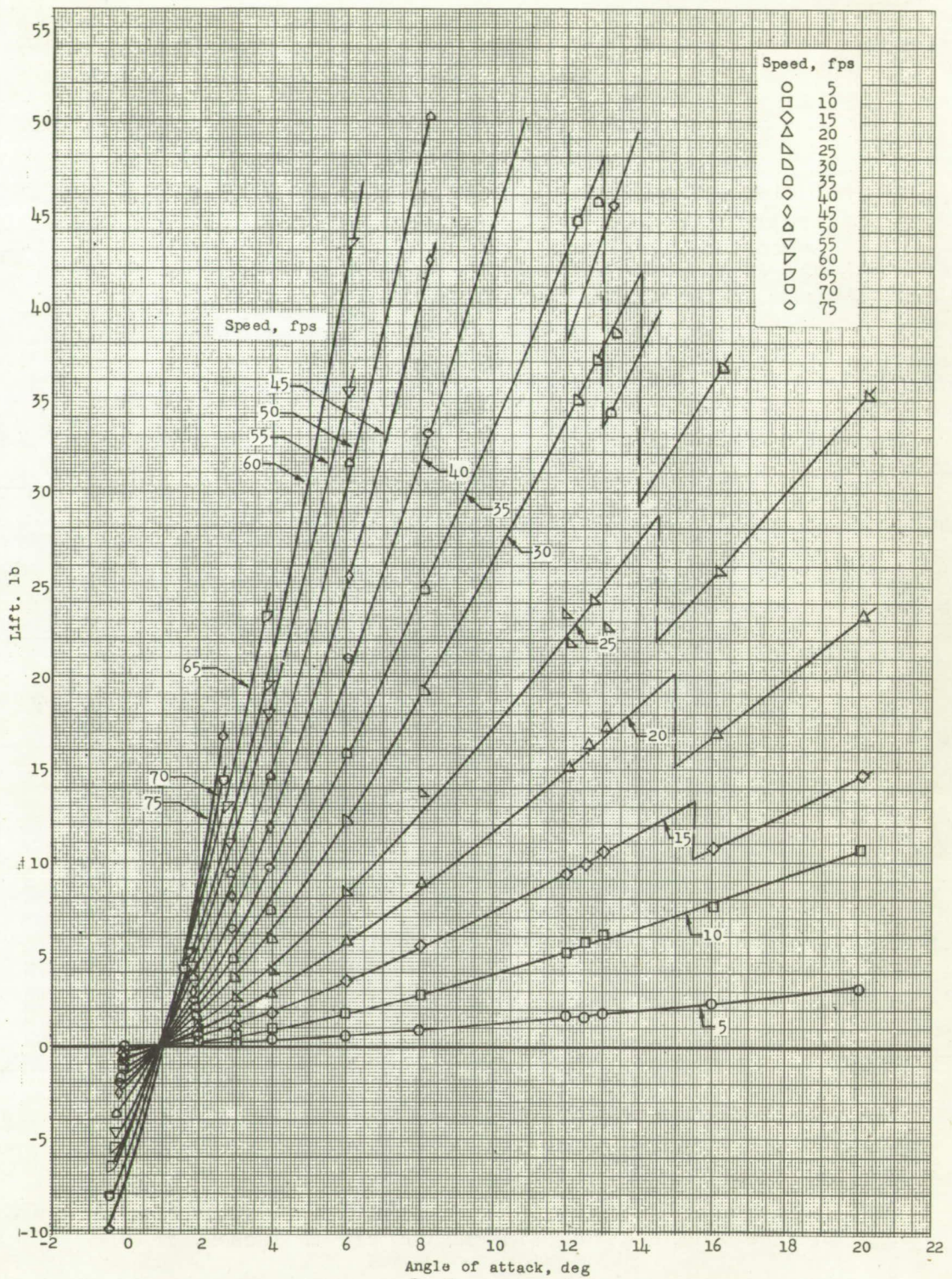
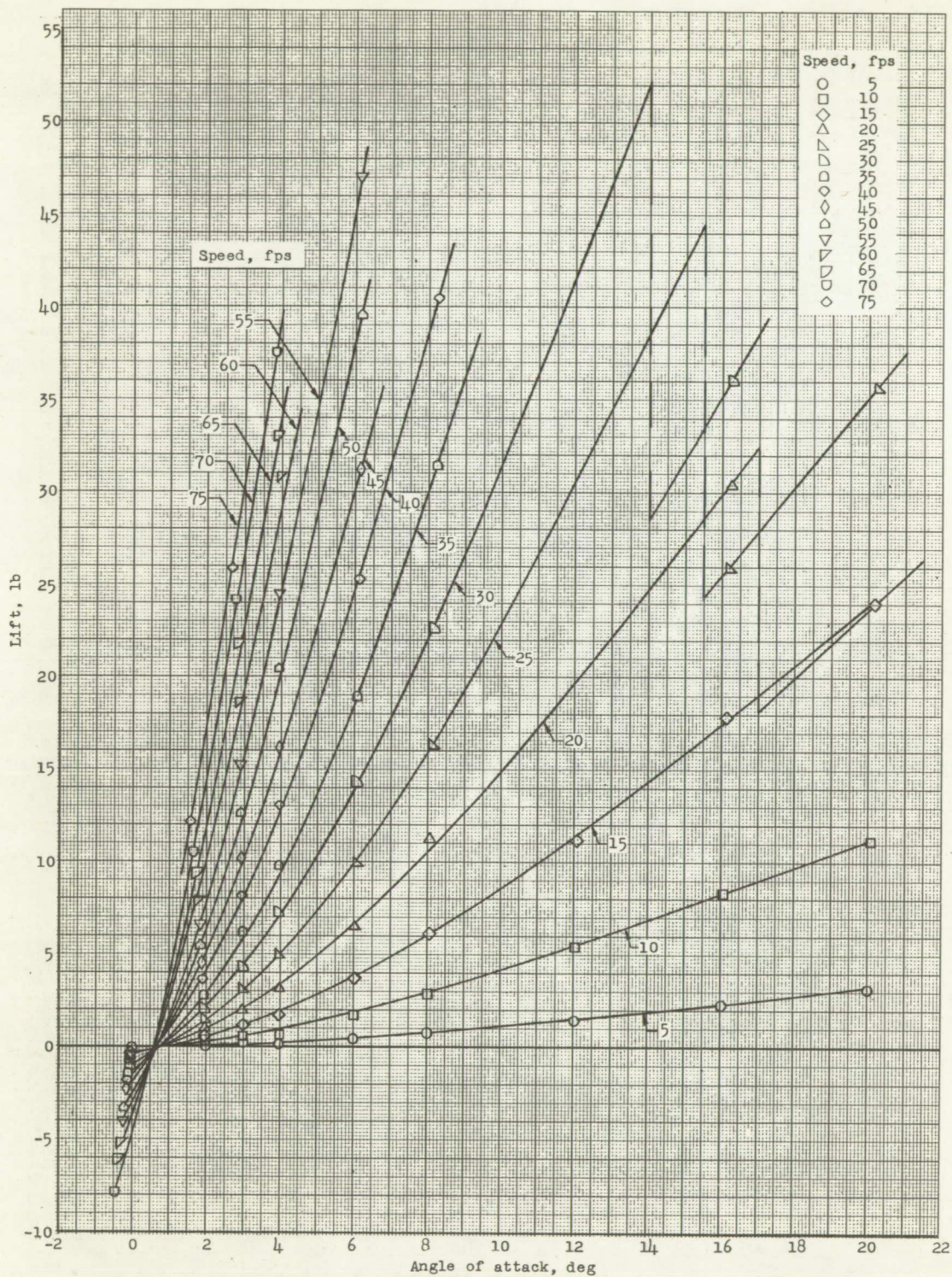


Figure 1.- Details of the aspect-ratio-0.125 flat plate mounted on a single strut. Dimensions are in inches.



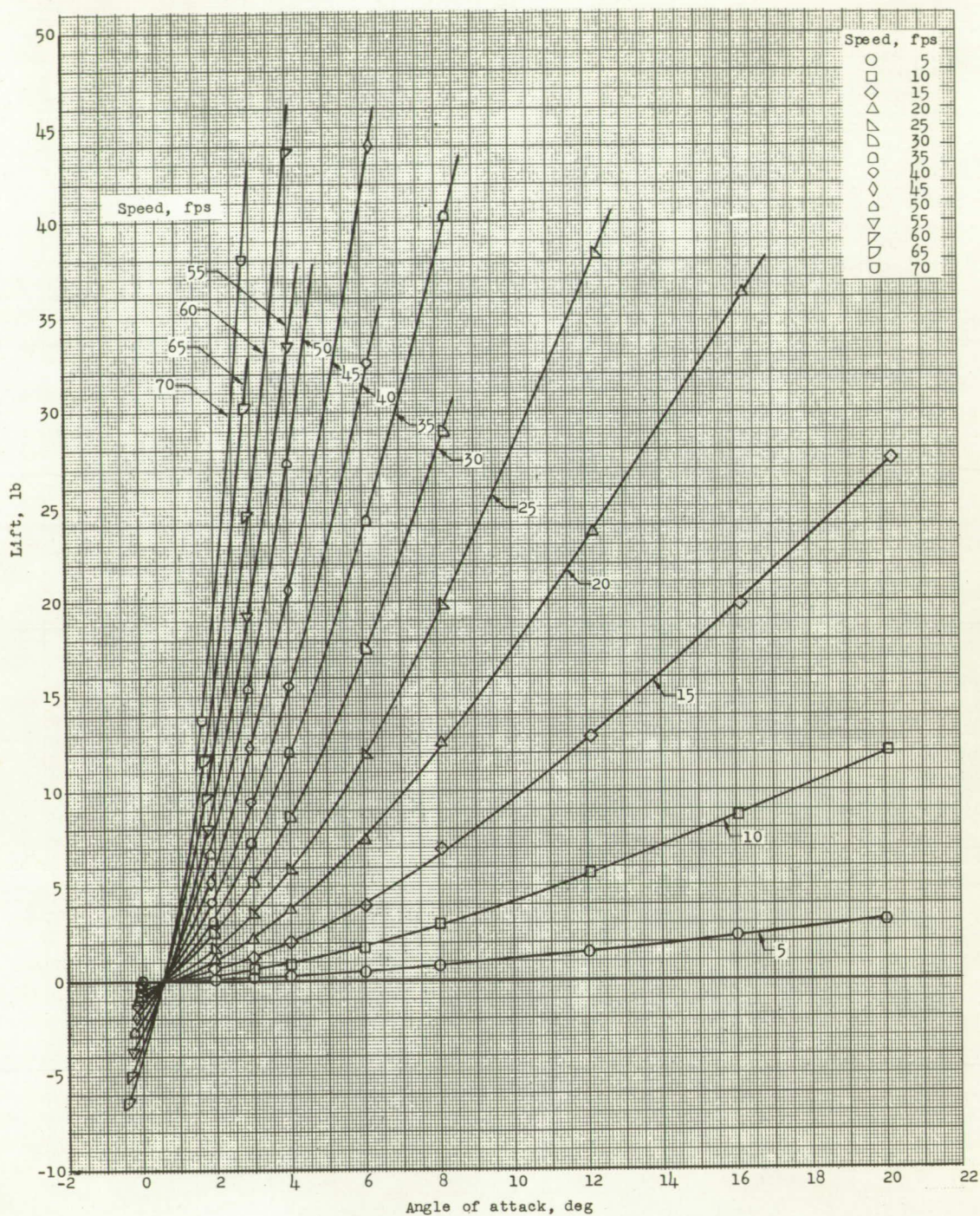
(a) Depth of submersion, 0.5 inch.

Figure 2.- Lift on the aspect-ratio-0.125 flat plate.



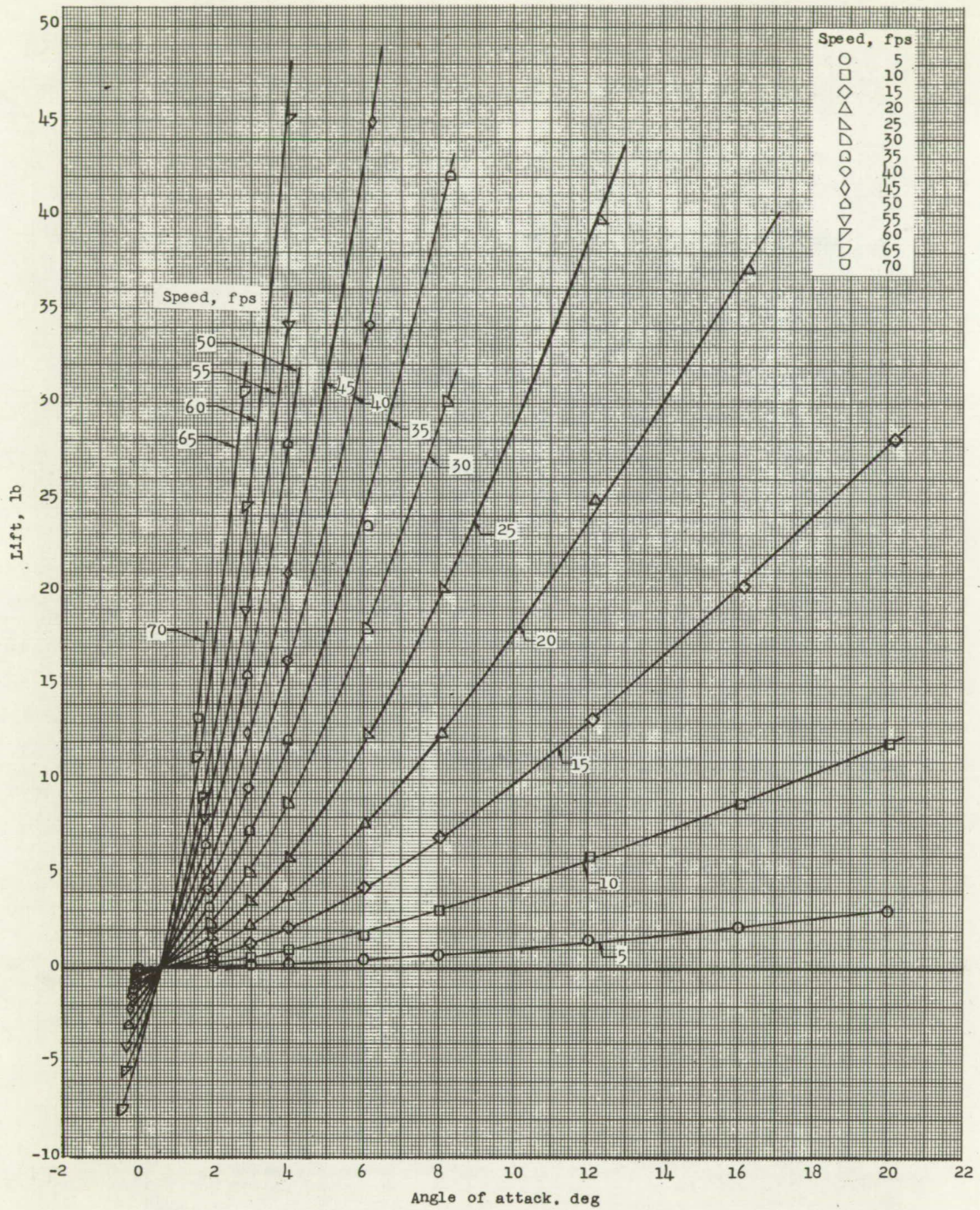
(b) Depth of submersion, 1.0 inch.

Figure 2.- Continued.



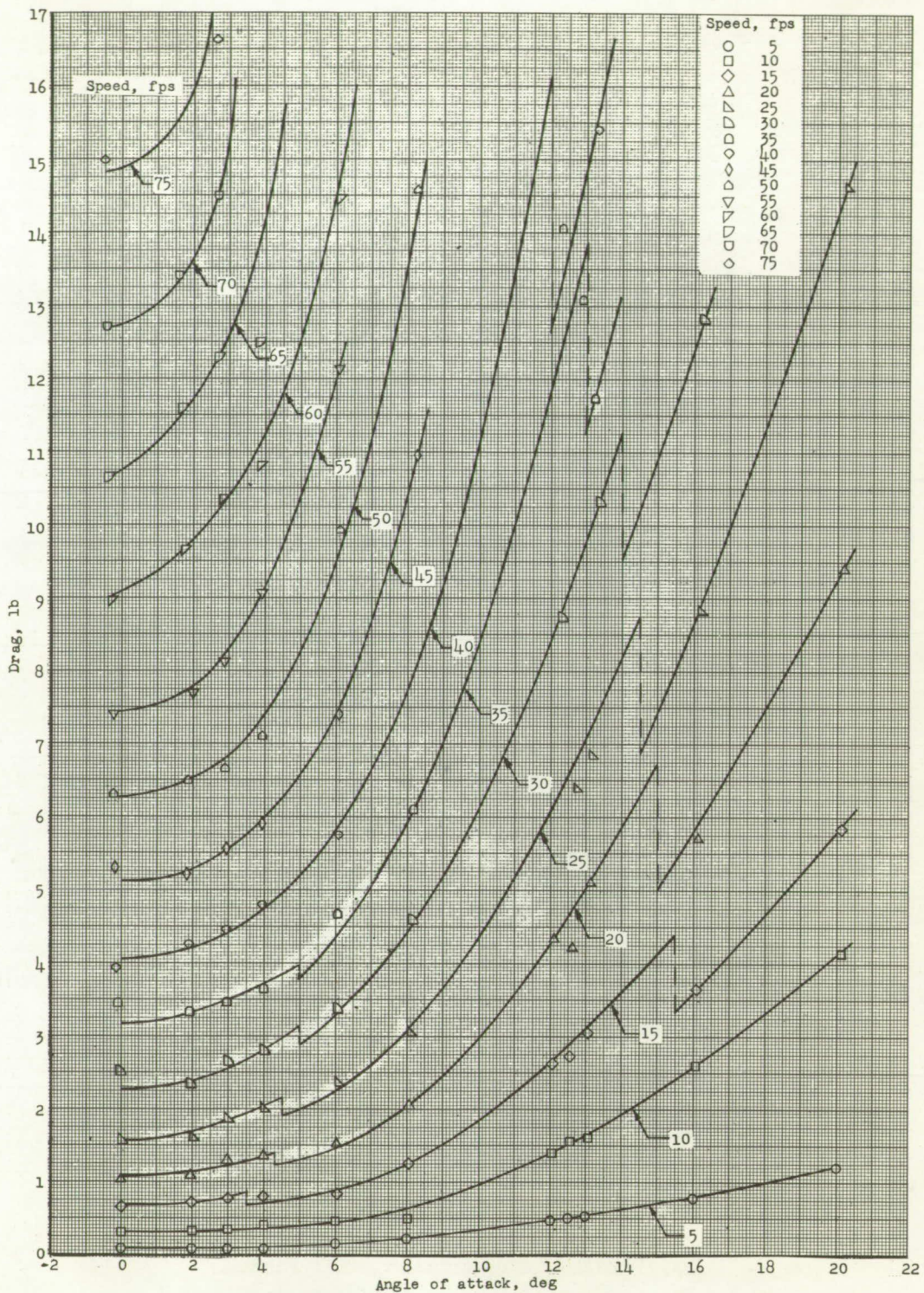
(c) Depth of submersion, 3.0 inches.

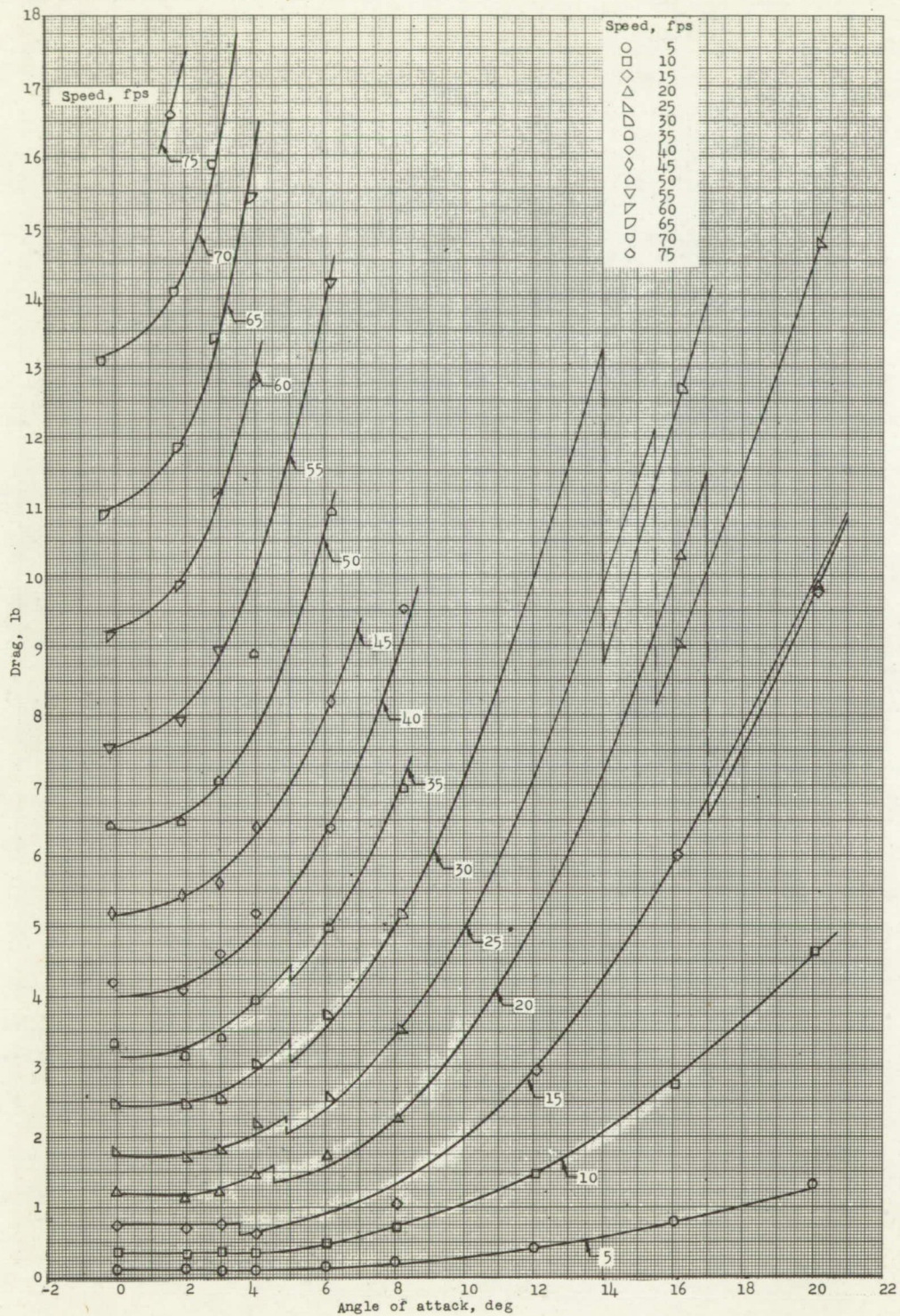
Figure 2.- Continued.



(d) Depth of submersion, 6.0 inches.

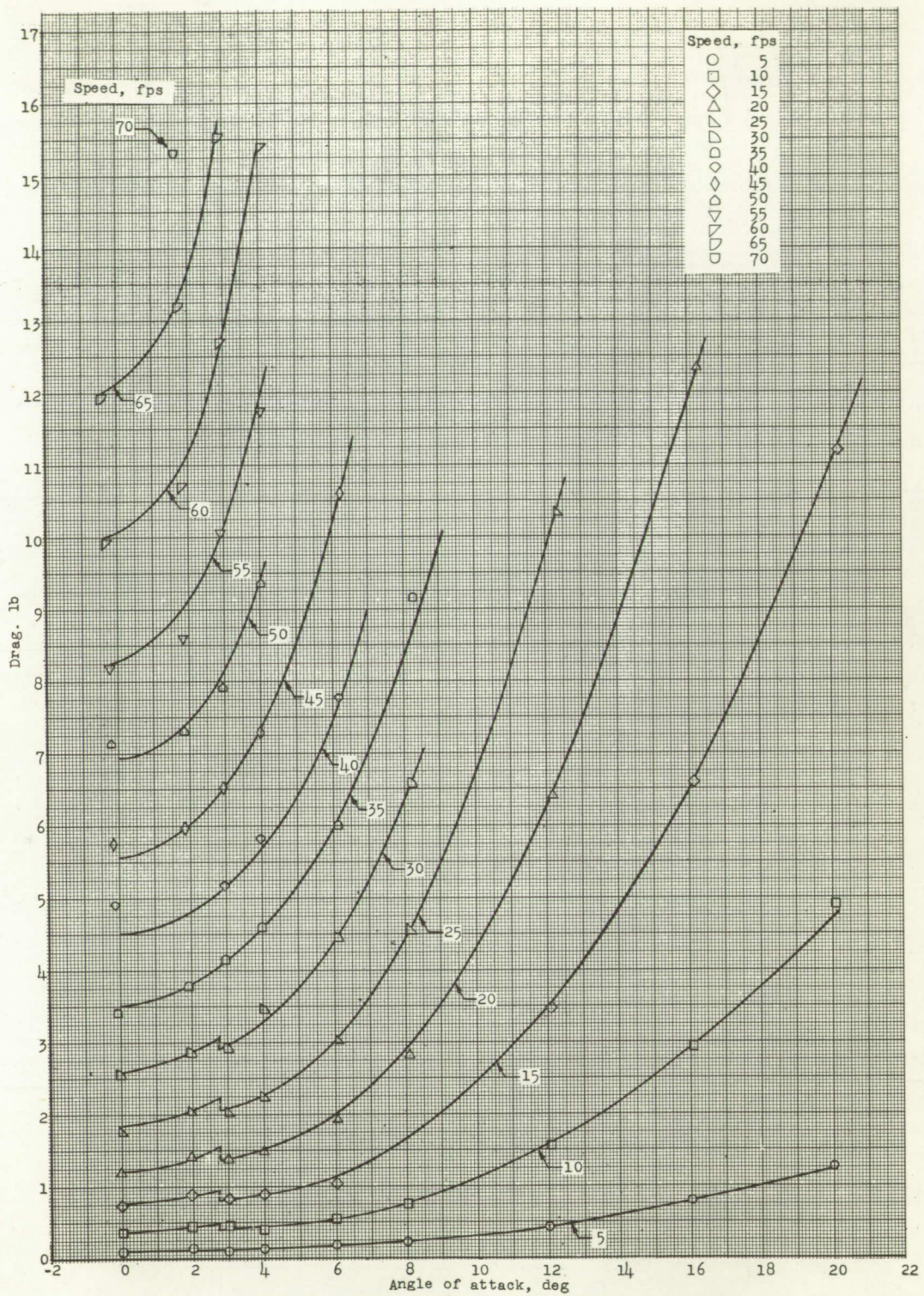
Figure 2.- Concluded.





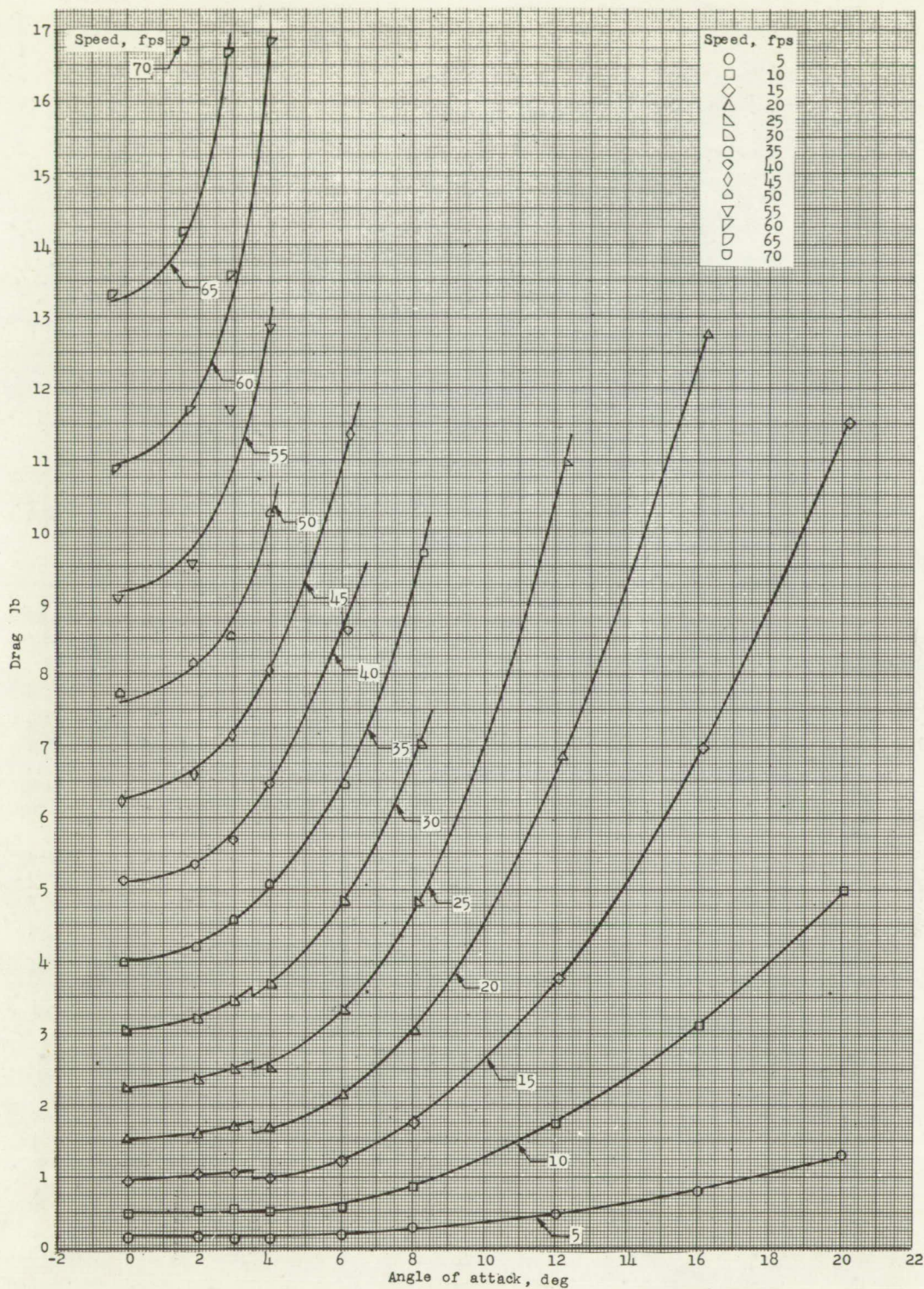
(b) Depth of submersion, 1.0 inch.

Figure 3.- Continued.



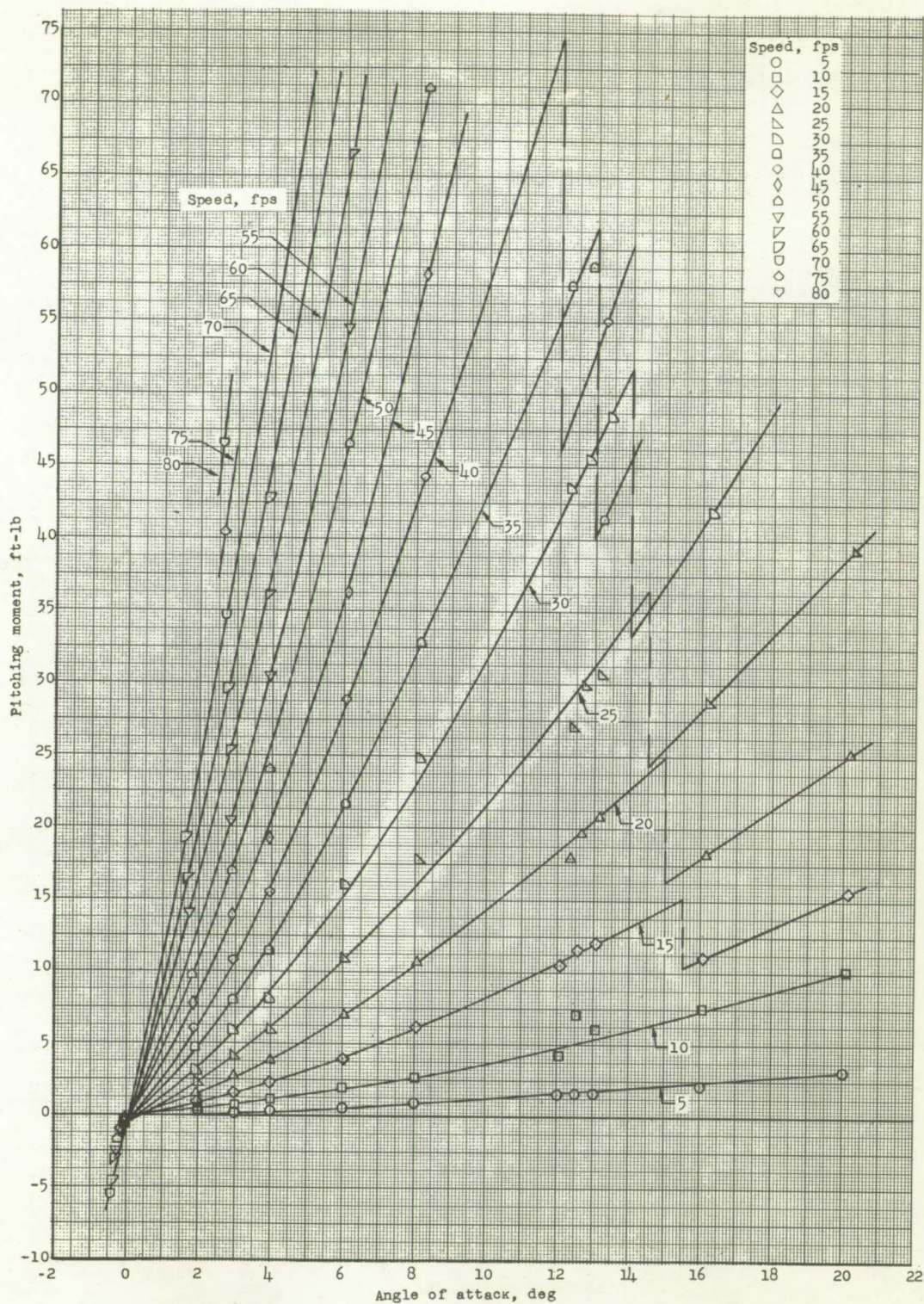
(c) Depth of submersion, 3.0 inches.

Figure 3.- Continued.



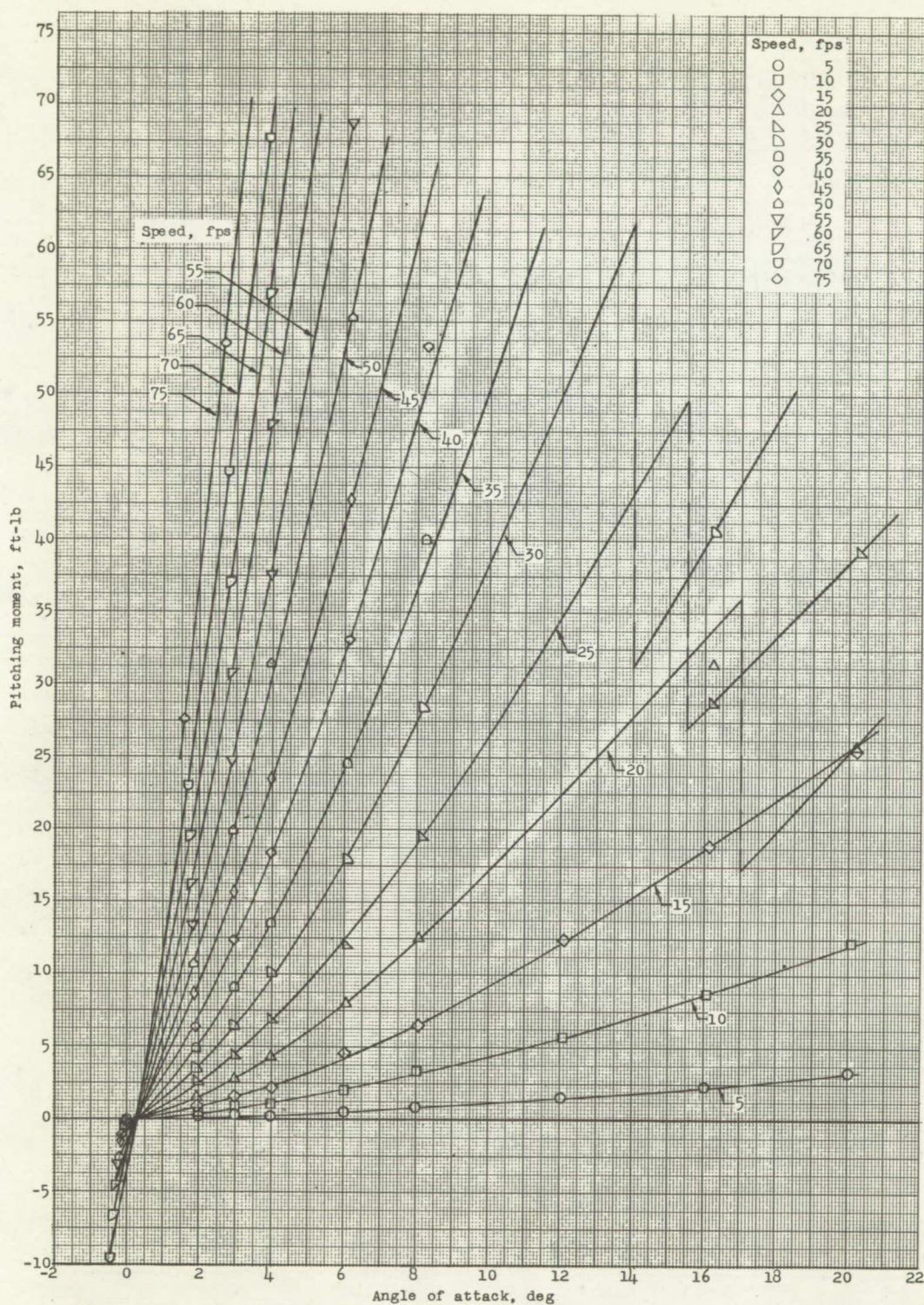
(d) Depth of submersion, 6.0 inches.

Figure 3.- Concluded.



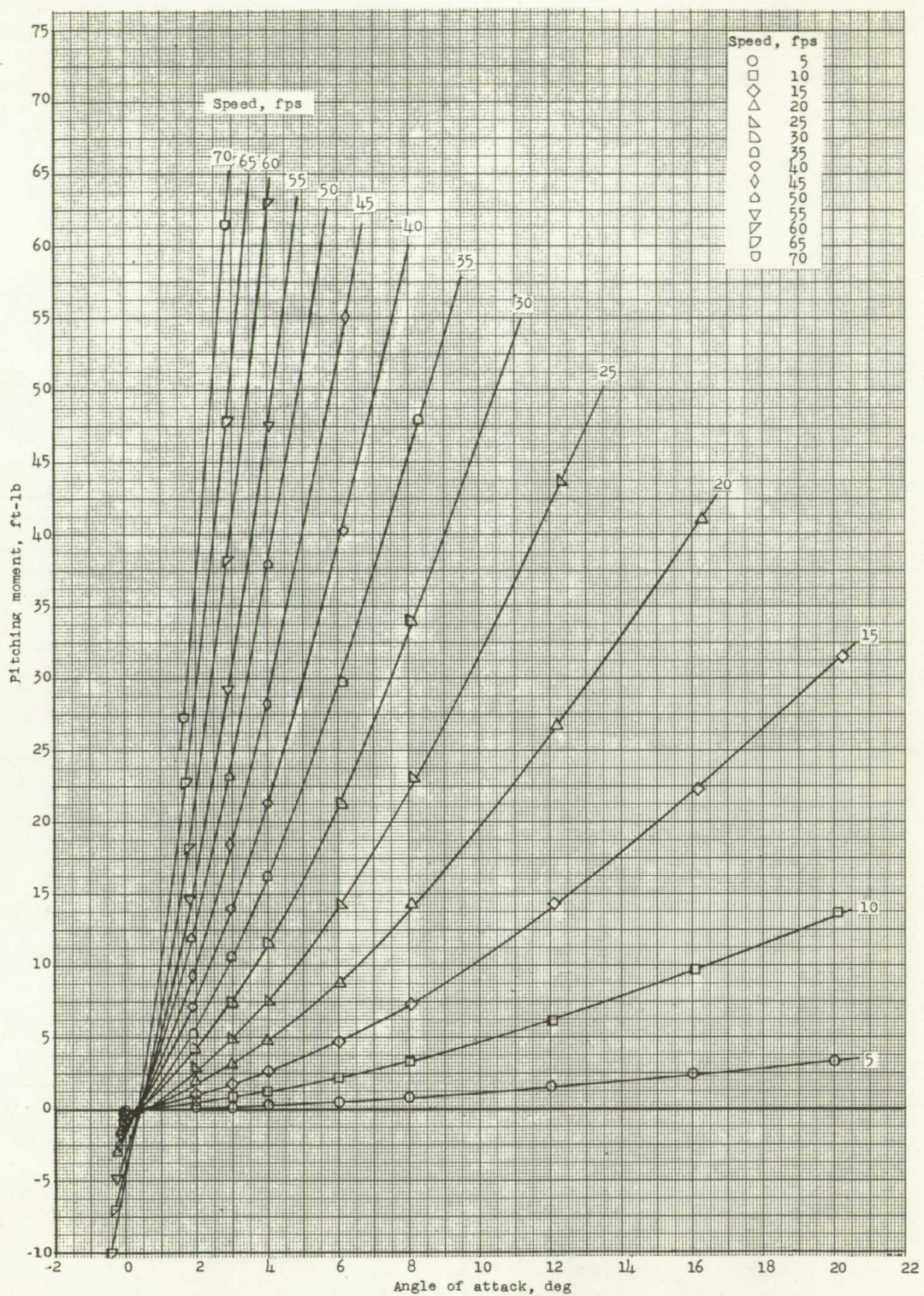
(a) Depth of submersion, 0.5 inch.

Figure 4.- Pitching moment on the aspect-ratio-0.125 flat plate.



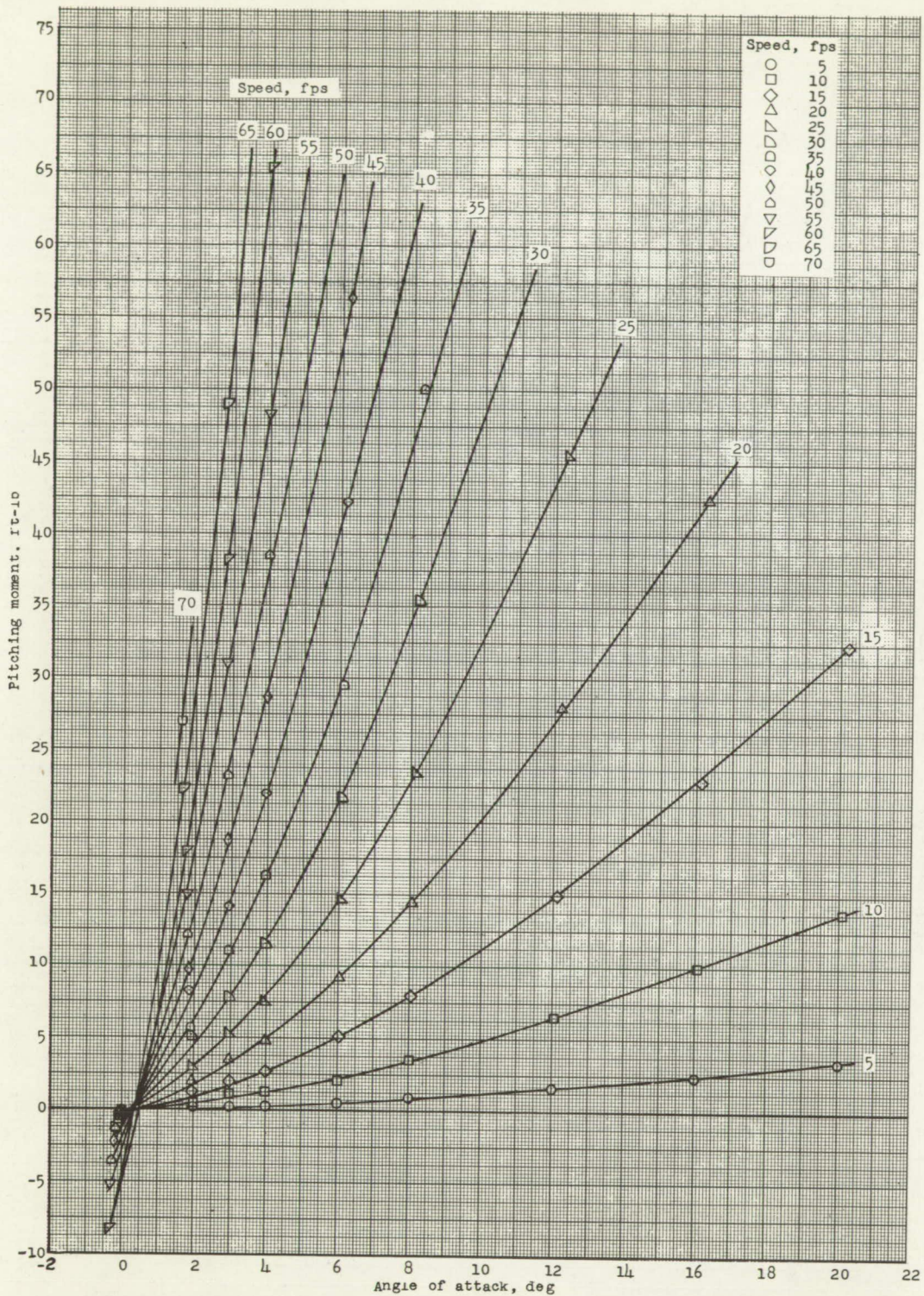
(b) Depth of submersion, 1.0 inch.

Figure 4.- Continued.



(c) Depth of submersion, 3.0 inches.

Figure 4.- Continued.



(d) Depth of submersion, 6.0 inches.

Figure 4.- Concluded.

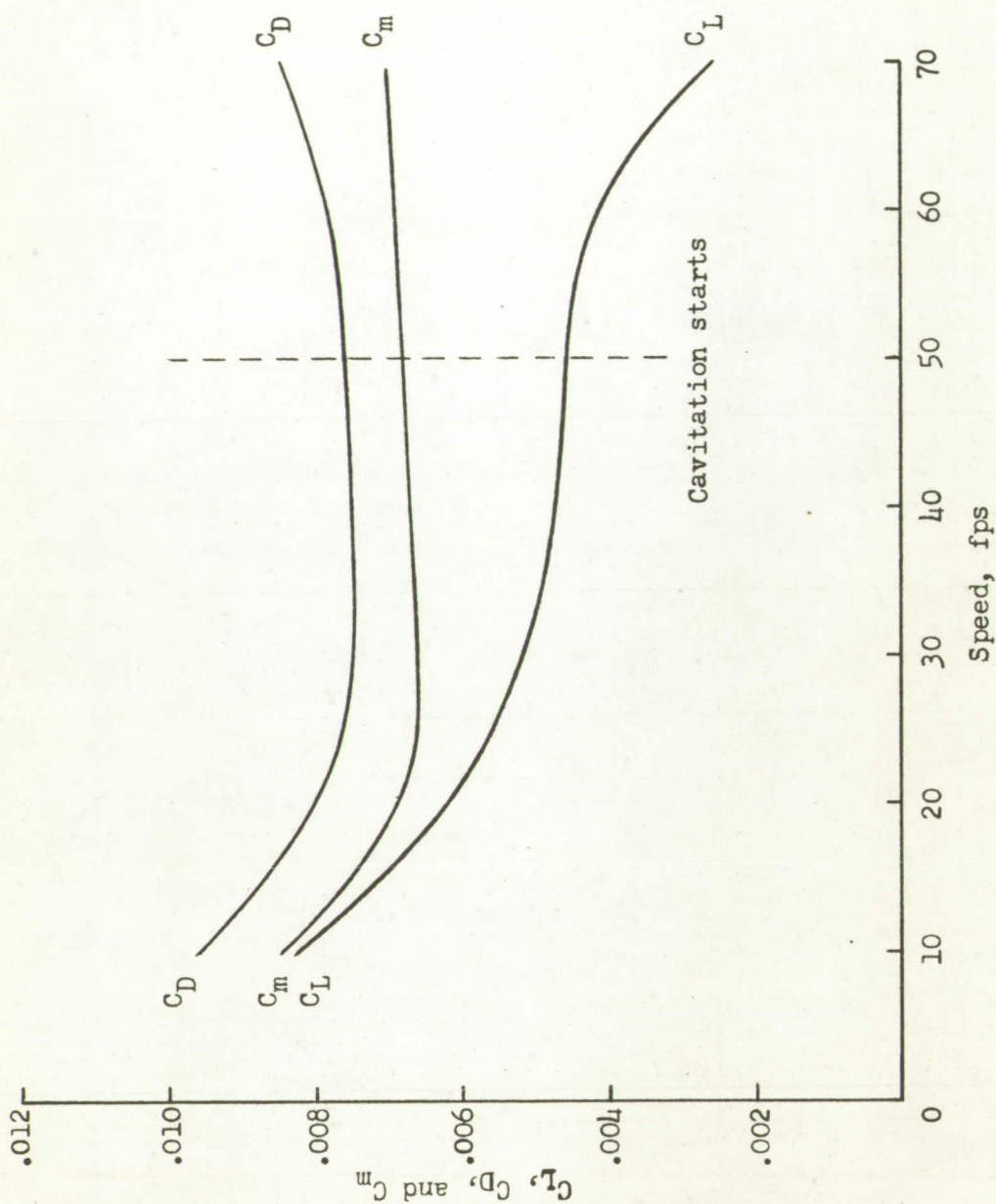


Figure 5.- Effect of the formation of cavitation on the force and moment characteristics for the aspect-ratio-0.125 flat plate at an angle of attack of 2° and a depth of submersion of 0.5 inch.

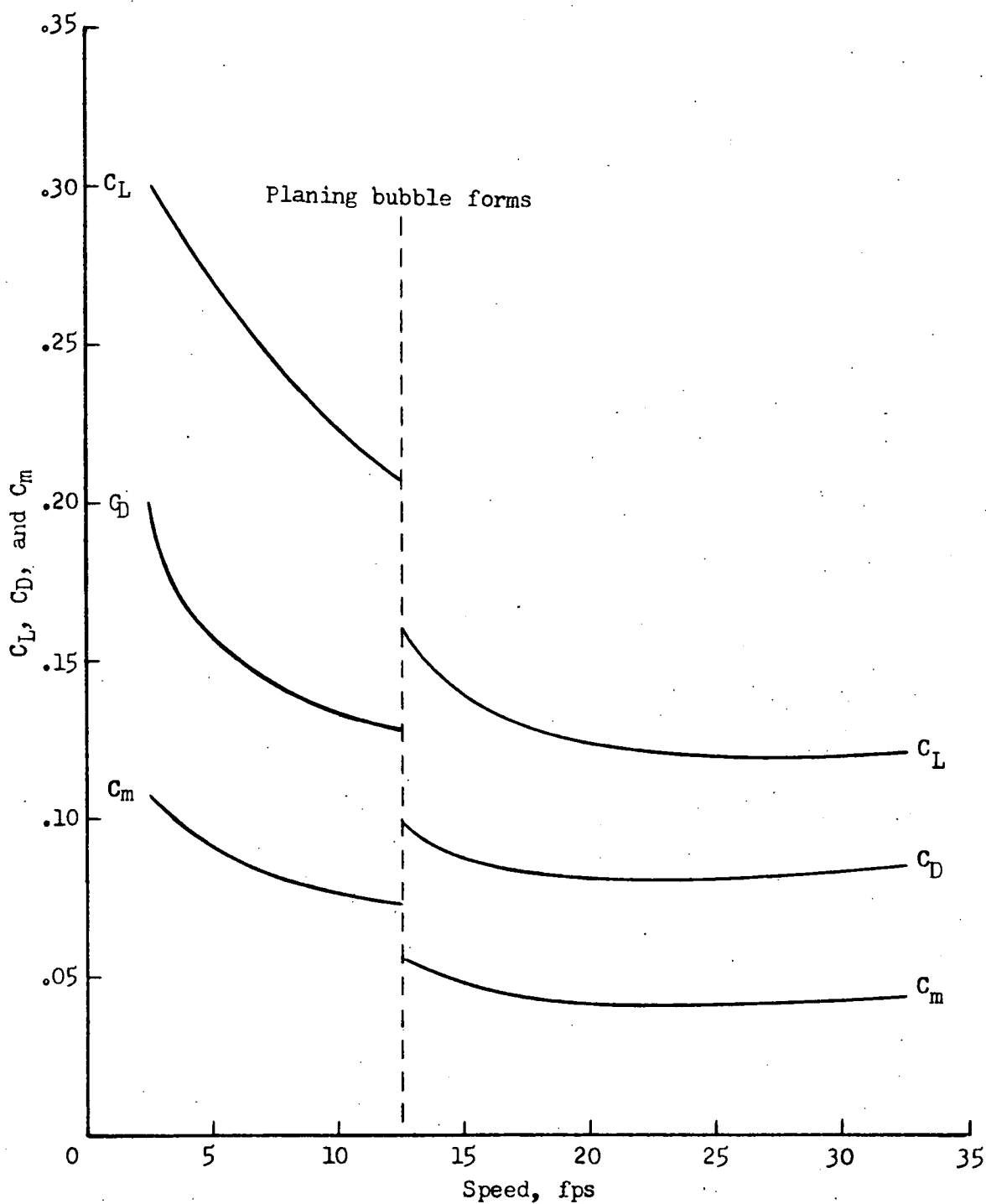


Figure 6.- Effect of the formation of the planing bubble on the force and moment characteristics for the aspect-ratio-0.125 flat plate at an angle of attack of 16° and a depth of submersion of 0.5 inch.

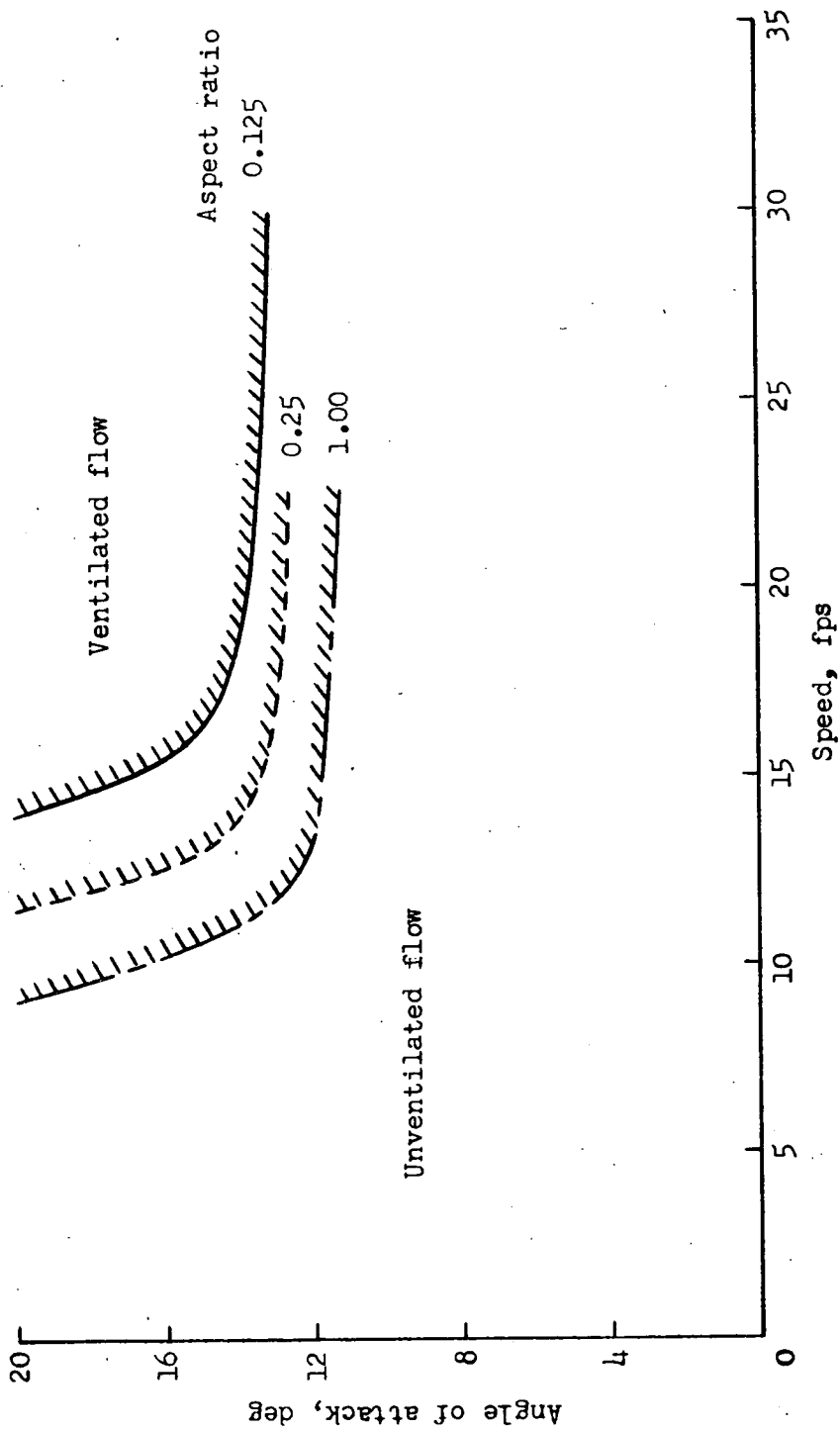


Figure 7.- Ventilation boundaries for the low-aspect-ratio flat plates at a depth of 0.5 inch.

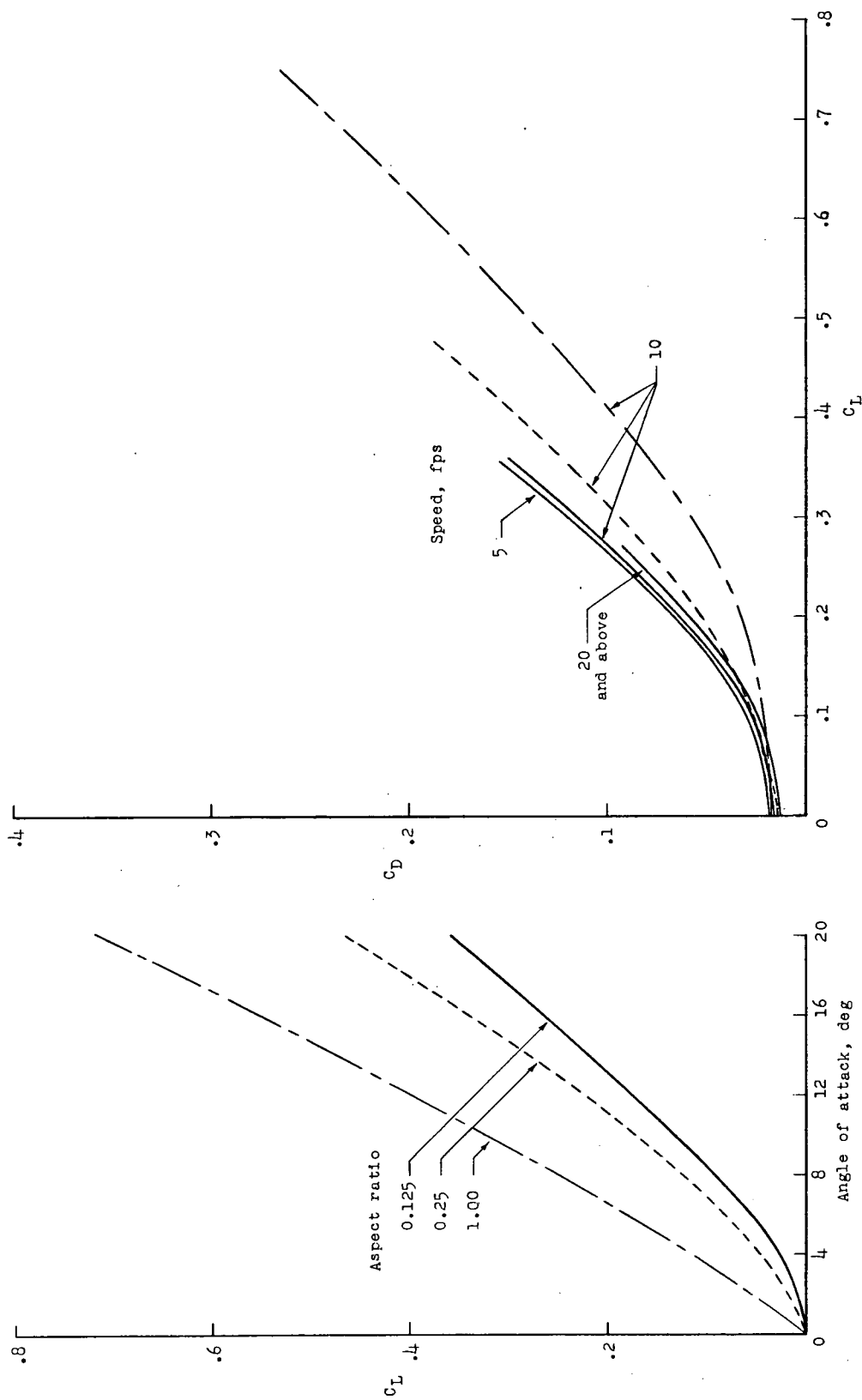
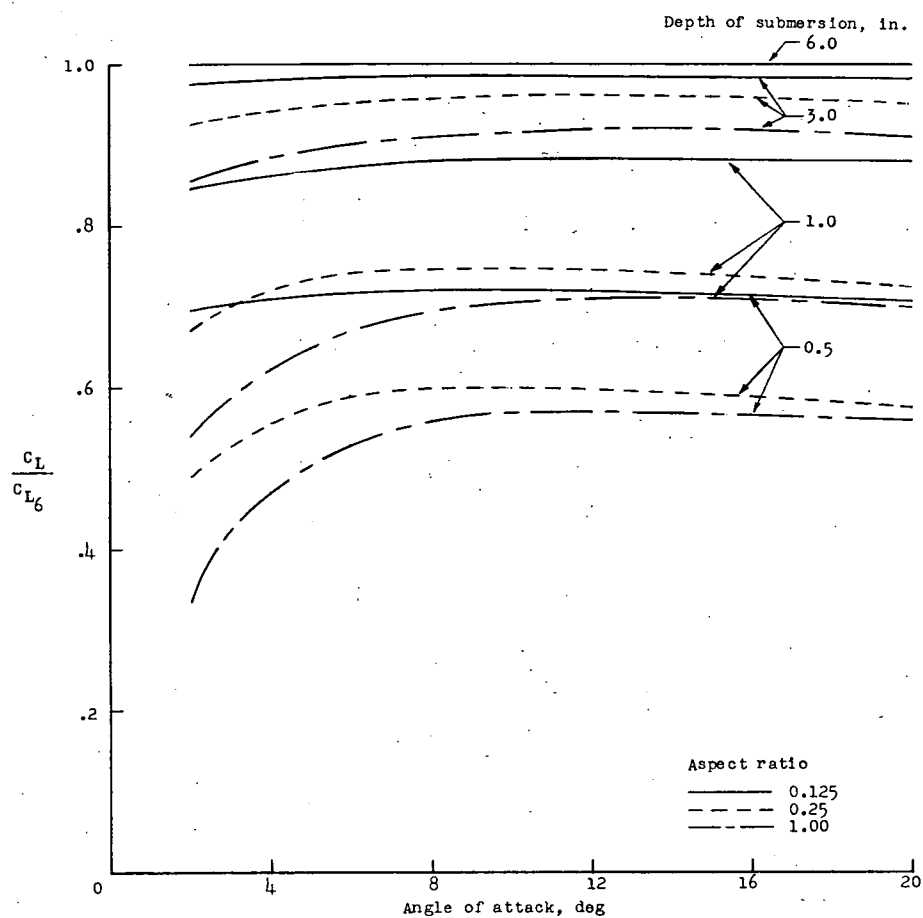
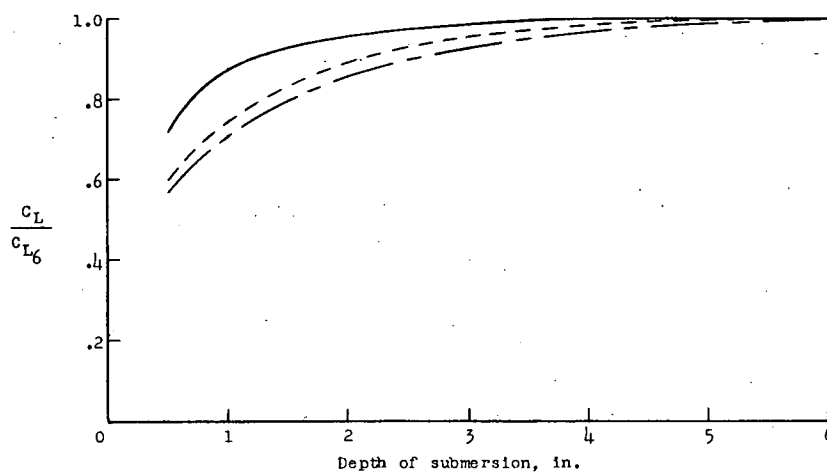


Figure 8.- The lift and drag characteristics of the low-aspect-ratio flat plates at a depth of 6.0 inches.

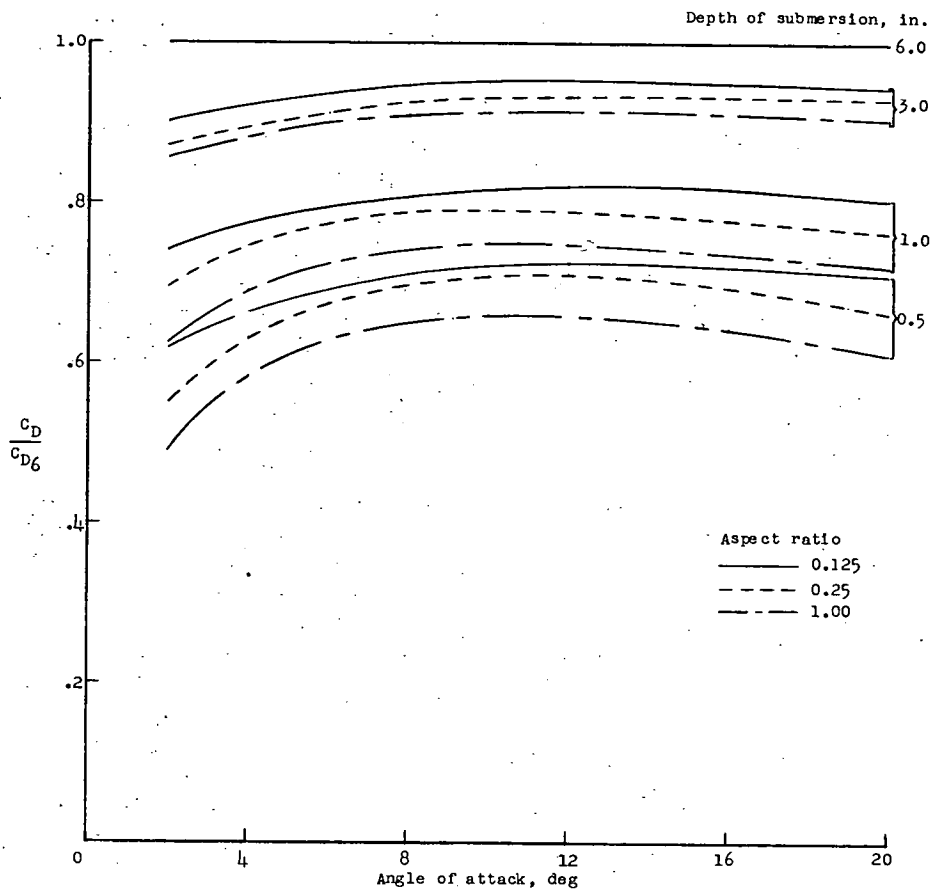


(a) Effect of angle of attack.

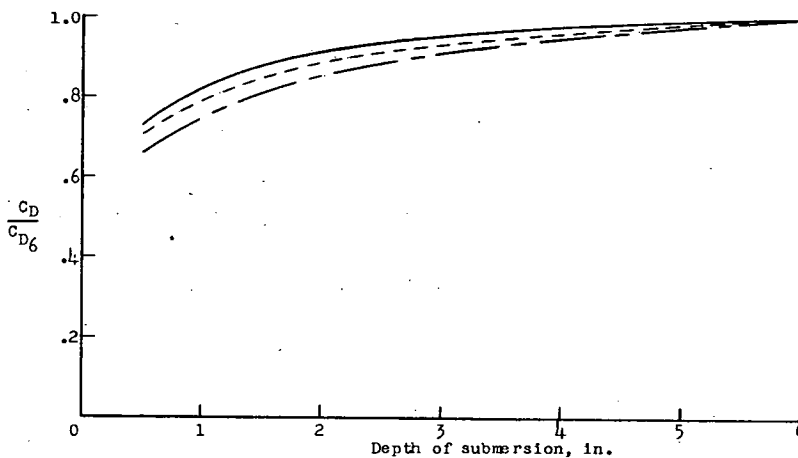


(b) Effect of depth of submersion (angle of attack, 12°).

Figure 9.- The variation of the lift characteristics due to changing depth of submersion.



(a) Effect of angle of attack.



(b) Effect of depth of submersion (angle of attack, 12°)

Figure 10.- The variation of the drag characteristics due to changing depth of submersion.

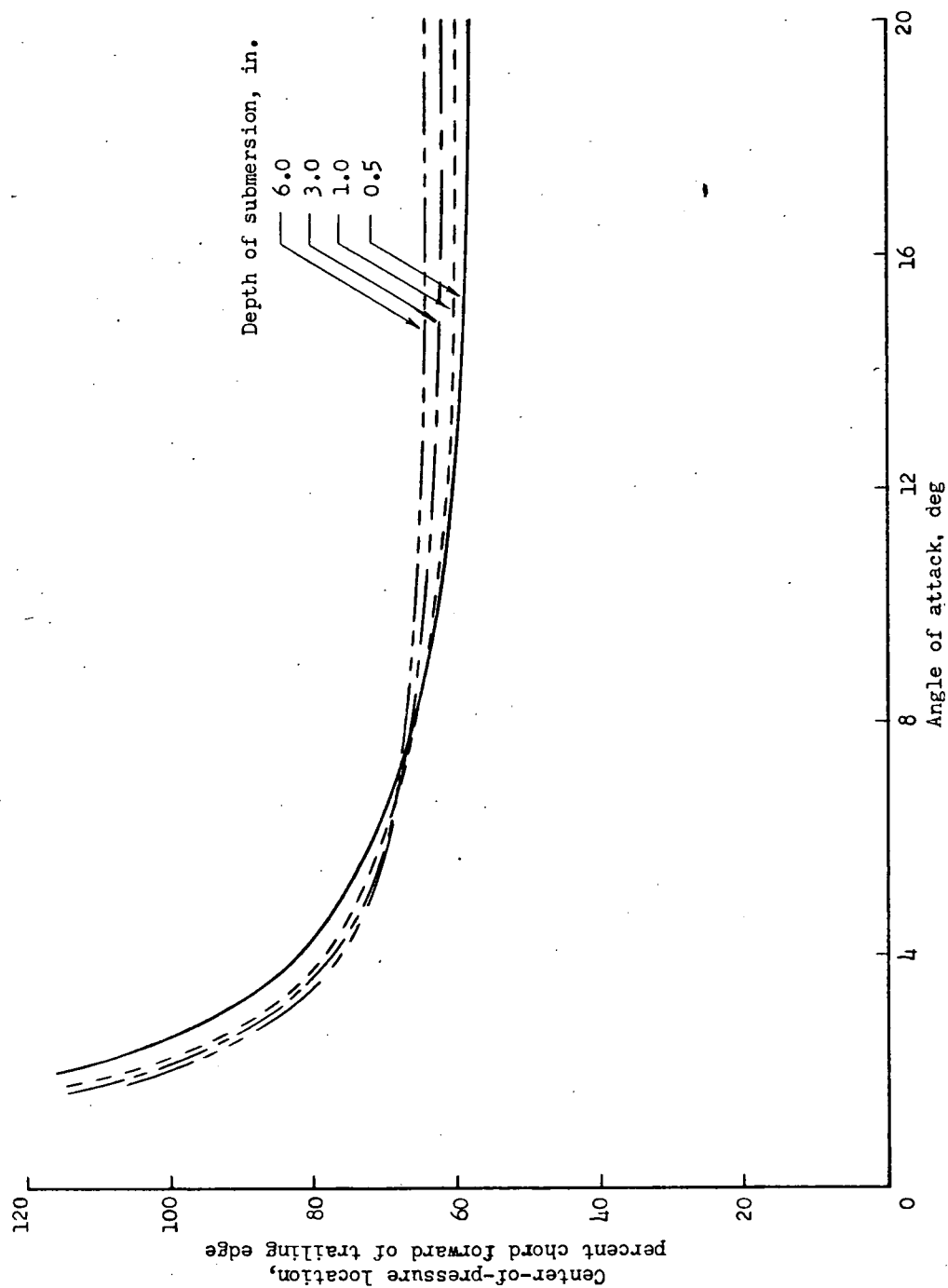


Figure 11.- The location of the center of pressure as a function of the angle of attack and the depth of submersion for the aspect-ratio-0.125 flat plate.

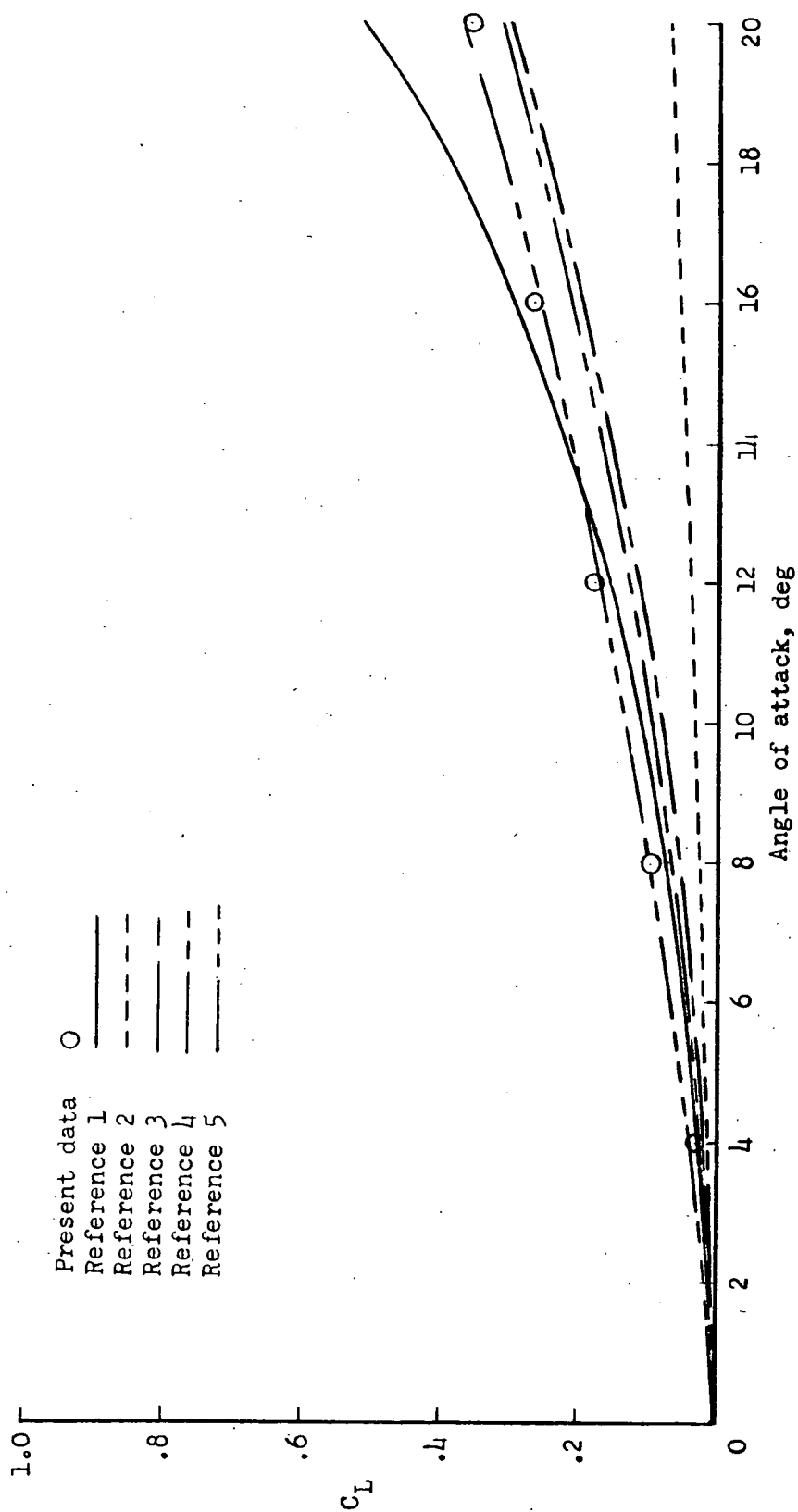


Figure 12.- Comparison between experimental and theoretical lift coefficients for the aspect-ratio-0.125 flat plate at a depth of submersion of 6.0 inches.

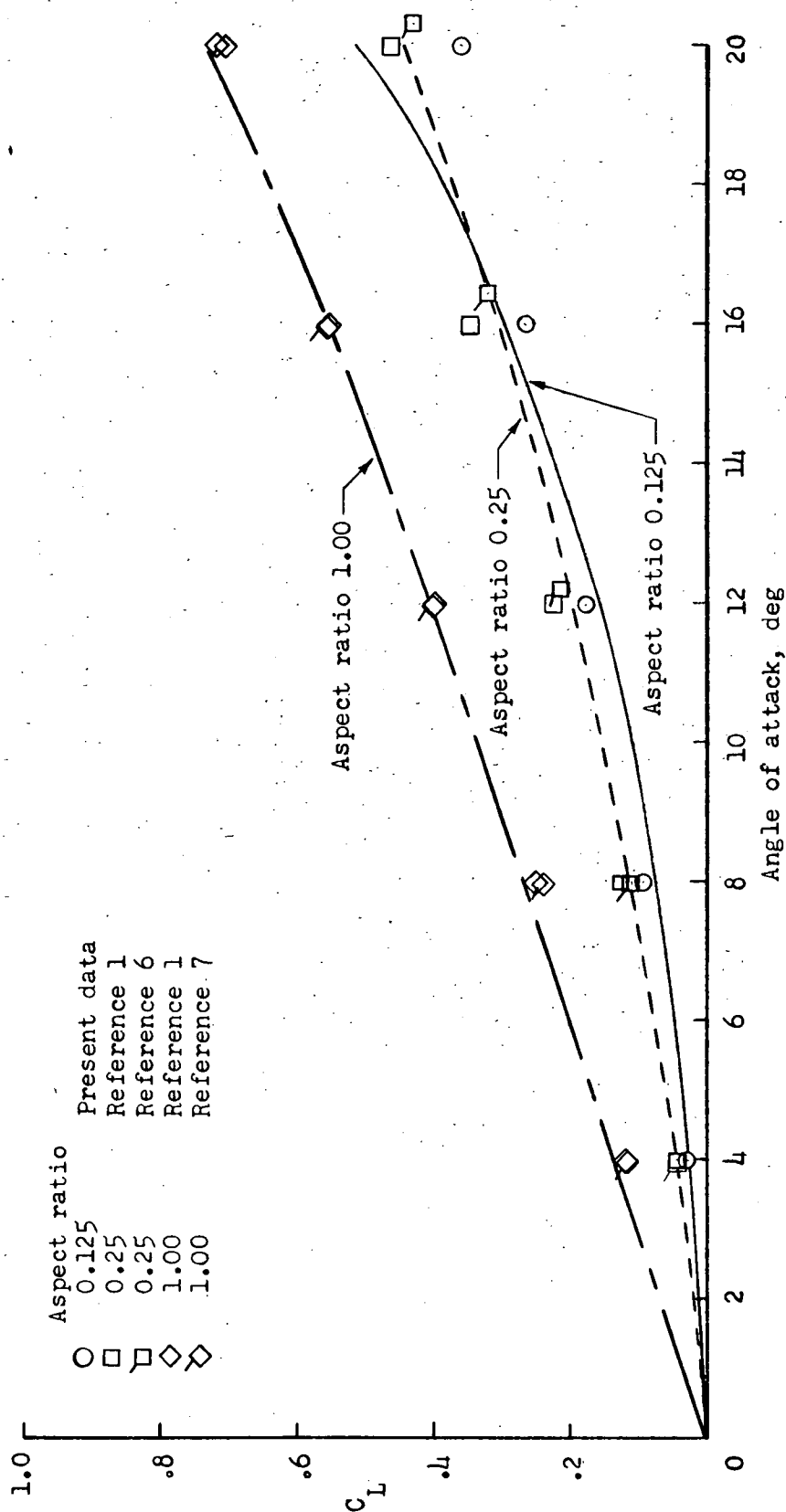


Figure 13.- Comparison between the theory of reference 1 and experimental data for the low-aspect-ratio flat plates at a depth of submersion of 6.0 inches.